

## **North Pacific Acoustic Laboratory: Scripps Institution of Oceanography**

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## **LONG-TERM GOALS**

The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering due to internal waves and other ocean processes limits the temporal and spatial coherence of the received signal. The objectives of the North Pacific Acoustic Laboratory (NPAL) program are to understand the basic physics of low-frequency, long-range, broadband propagation, the effects of environmental variability on signal stability and coherence, and the fundamental limits to signal processing at long-range imposed by ocean processes. The long-term goal is to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods, to capitalize on the three-dimensional character of the sound and noise fields.

## **OBJECTIVES**

The scientific objectives are:

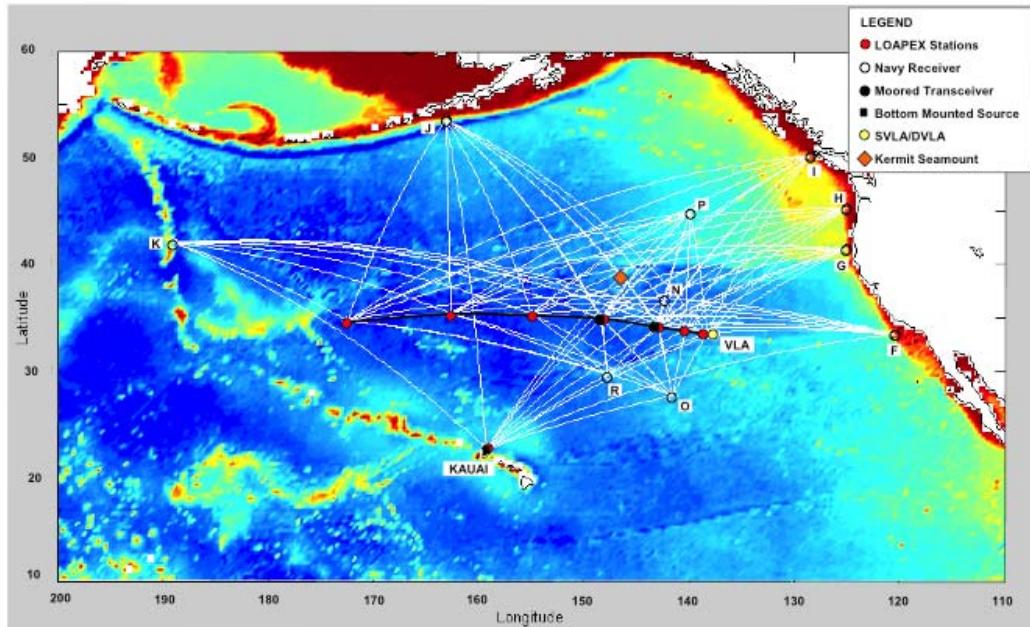
- To study 3-D coherence (horizontal, vertical, and temporal) of long-range, low-frequency resolved rays and modes

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- To explore the range and frequency dependence of the fluctuation statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments
- To understand the surprisingly large amount of acoustic scattering into the geometric shadow zone beneath caustics previously seen with bottom-mounted SOSUS receivers (shadow-zone arrivals)
- To elucidate the relative roles of internal waves, ocean spice, and internal tides in causing acoustic fluctuations
- To document the spatial and temporal variability of ambient noise on ocean basin scales
- To improve basin-scale ocean nowcasts via assimilation of acoustic travel-time and other data into models
- To study acoustic scattering and diffraction from bathymetry

## APPROACH

NPAL employs a combination of experiment, data analysis, and simulations to address the issues outlined above. Previous NPAL-related research is summarized in Worcester and Spindel (2005).



*Fig. 1. Overall geometry of the 2004–2005 NPAL experiment. The 250-Hz moored transceivers (black) were located 500 and 1000 km west of the SVLA/DVLA receivers (yellow). The LOAPEX transmission stations (red) extended roughly westward from the VLAs to a maximum range of about 3200 km. A final LOAPEX station was located near the Kauai source. The BASSEX towed array was deployed close to Kermit Roosevelt Seamount (orange), as well as in the vicinity of the Kauai source. U. S. Navy SOSUS receivers that received the various transmissions are shown in white.*

The principal experimental effort during the current phase of NPAL is a long-range ocean acoustic propagation experiment with three closely related components, named *SPICE04*, *LOAPEX* (*Long-range Ocean Acoustic Propagation EXperiment*), and *BASSEX* (*Basin Acoustic Seamount Scattering EXperiment*) (Fig. 1), that was conducted during 2004–2005. SIO had primary responsibility for *SPICE04*, for which two 250-Hz broadband acoustic transceiver moorings and two autonomous vertical line array (VLA) receivers were installed for about one year. APL-UW had primary responsibility for *LOAPEX*, during which an approximately 75-Hz source lowered from shipboard during September–October 2004 transmitted to the VLA receivers at ranges varying from 50 km to 3200 km, as well as from an eighth station near the island of Kauai. MIT and OASIS had primary responsibility for *BASSEX*, during which a towed horizontal array received the transmissions from the 250-Hz *SPICE04* sources, the 75-Hz *LOAPEX* source, and the ATOC/NPAL source north of Kauai. The geometry was chosen to keep the *SPICE04* and *LOAPEX* paths entirely within the subtropical gyre. The VLA moorings were located between the Subarctic and Northern Subtropical Fronts and to the west of the complicated California Current region.

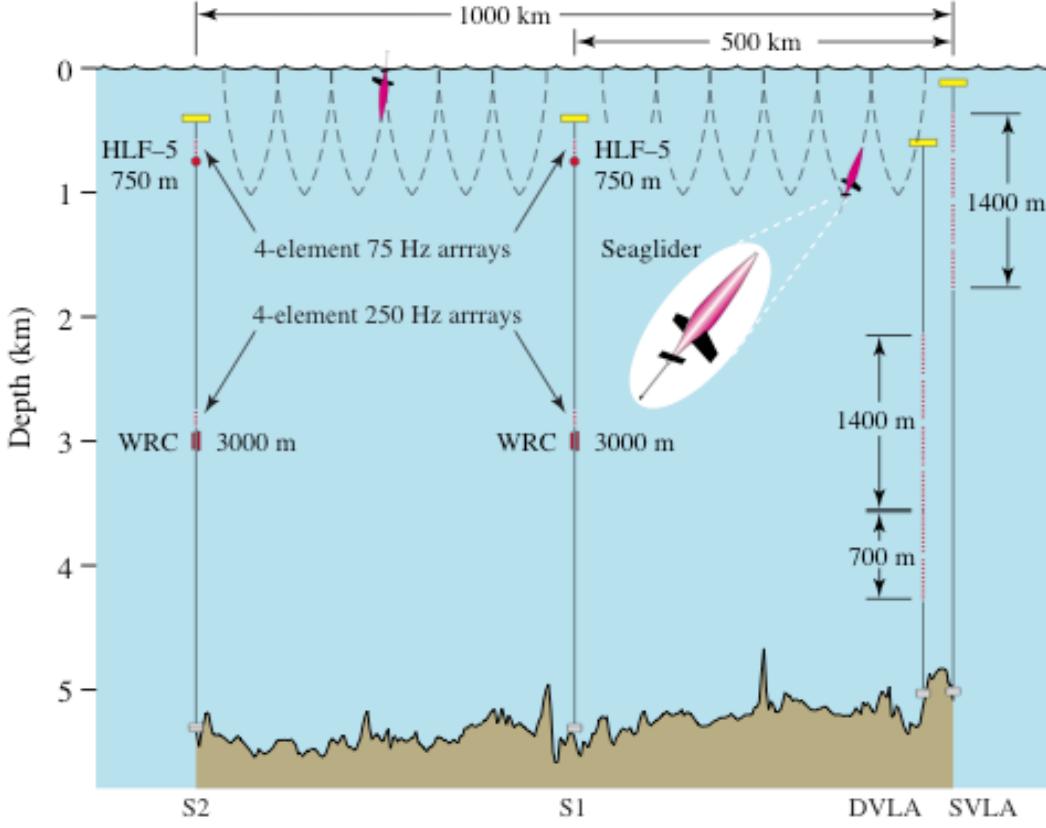
In addition, the *SPICE04* and *LOAPEX* transmissions, as well as the continuing transmissions from the ATOC/NPAL source north of Kauai, were recorded at the U. S. Navy SOSUS receivers in the North Pacific. APL-UW has primary responsibility for continued operation of the Kauai source and SOSUS receivers. Ambient noise data are also being recorded at the SOSUS receivers.

This report summarizes SIO's efforts.

## WORK COMPLETED

The two autonomous vertical line array (VLA) receivers and two 250-Hz broadband acoustic transceiver moorings that were deployed from the *R/V Roger Revelle* during 26 May–18 June 2004 were recovered during a research cruise on the *R/V Thomas G. Thompson* from 6–26 June 2005. Four Ocean Bottom Seismometers (OBS) deployed at the VLA site during the *LOAPEX* cruise for R. Stephen (WHOI) and J. Colosi (NPS) were also recovered.

*Vertical Line Array (VLA) Receivers.* The Shallow VLA (SVLA) had a 40-element, 1400-m long array centered approximately on the sound channel axis (350–1750 m nominal) and located to optimize resolution of acoustic modes 1–10 at 75 Hz. Both the upper and lower AVATOC data acquisition systems, which recorded data from the upper and lower 700 m sections of the array, functioned normally throughout the approximately one-year deployment. The Deep VLA (DVLA) combined a 40-element, 1400-m long array (2150–3550 m nominal) with a 20-element, 700-m long array (3570–4270 m nominal) to span the lower caustics in the acoustic arrival pattern. It contained upper, middle, and lower AVATOC data acquisition systems, which recorded data from the upper, middle, and lower 700-m sections of the array, respectively. The upper AVATOC fell roughly six feet to the deck when the bridal being used to bring the instrument on board failed during recovery. Nonetheless, the AVATOC was still running and was found to have functioned normally throughout the deployment. We were able to read the data from two of the four data disks. (The remaining two disks have been sent to a disk recovery service, but it seems unlikely that it will be possible to recover data from them.) The AVATOC data acquisition systems write receptions in rotation to the four disks, and data are therefore available throughout the one-year deployment. The middle AVATOC was found to have had a slow leak through an underwater connectors, and no useful acoustic data were recorded. The bottom AVATOC functioned normally throughout the deployment.



**Fig. 2. SPICE04 experimental geometry.** Two transceiver moorings (S1 and S2) were deployed 500 and 1000 km from two autonomous vertical line array receivers (SVLA and DVLA). One receiving array had a 1400-m aperture spanning the sound-channel axis (Shallow VLA), and the other had a 2100-m aperture spanning a number of lower turning points (Deep VLA). The SVLA and DVLA were separated by about 3 nm. The Seaglider shown is one of several methods used to obtain the necessary environmental data.

The SVLA and the top and bottom sections of the DVLA successfully recorded transmissions from (i) the 250-Hz moored sources, (ii) the 75-Hz LOAPEX source, and (iii) the 75-Hz ATOC/NPAL source north of Kauai.

**Moored 250-Hz Transceivers.** Both transceiver moorings had (i) a 250-Hz HLF-5 source located at a nominal depth of 750 m, approximately on the sound channel axis, which transmitted broadband, phase-coded m-sequences; and (ii) a Webb Research Corporation (WRC) swept frequency source located at a nominal depth of 3000 m, approximately at the surface conjugate depth, which transmitted a linear FM sweep from 225–325 Hz. All of the transceivers had STAR (Simple Tomographic Acoustic Receiver) data acquisition systems and source controllers. Following deployment all four transceivers functioned normally until year day 335 of 2004, when a software bug (which has since been fixed) in the STAR receiver/controller caused all four transceivers to stop. An attempt was made to repair and/or replace one of the transceiver moorings on the *R/V New Horizon* during 6–19 March 2005, but a combination of poor weather and equipment problems prevented us from doing so.

The 250-Hz transmissions were therefore recorded by the VLA receivers, by the 250-Hz transceivers themselves, and by U.S. Navy SOSUS receivers for approximately five months, from June through November 2004. The transmissions were also recorded by the *BASSEX* horizontal towed array during September-October 2004.

*Environmental Measurements.* CTD and Underway CTD (UCTD) measurements were made along the path between the VLA receivers and moored sources during the *SPICE04* deployment cruise in June 2004 and during the *LOAPEX* cruise in September-October 2004, providing high-resolution measurements of the upper ocean both in spring, when the winter mixed layer was still relatively fully developed, and at the end of summer, when the summer thermocline was fully developed. A Seaglider autonomous vehicle deployed by APL-UW during the *LOAPEX* cruise also made measurements along the path beginning in September, before transiting to Kauai for recovery. Finally, a SeaSoar cruise during March 2005 measured upper ocean structure along the acoustic path when the winter mixed layer was fully formed (D. Rudnick, SIO), although the moored sources were no longer transmitting at that time. The goal is to separate the sound-speed fine structure into two component fields: (i) isopycnal tilt dominated by internal waves and (ii) “spicy” (cold-fresh to hot-salty) millifronts associated with upper ocean stirring, so that the relative roles of internal waves and spice in the scattering of the NPAL transmissions can be evaluated.

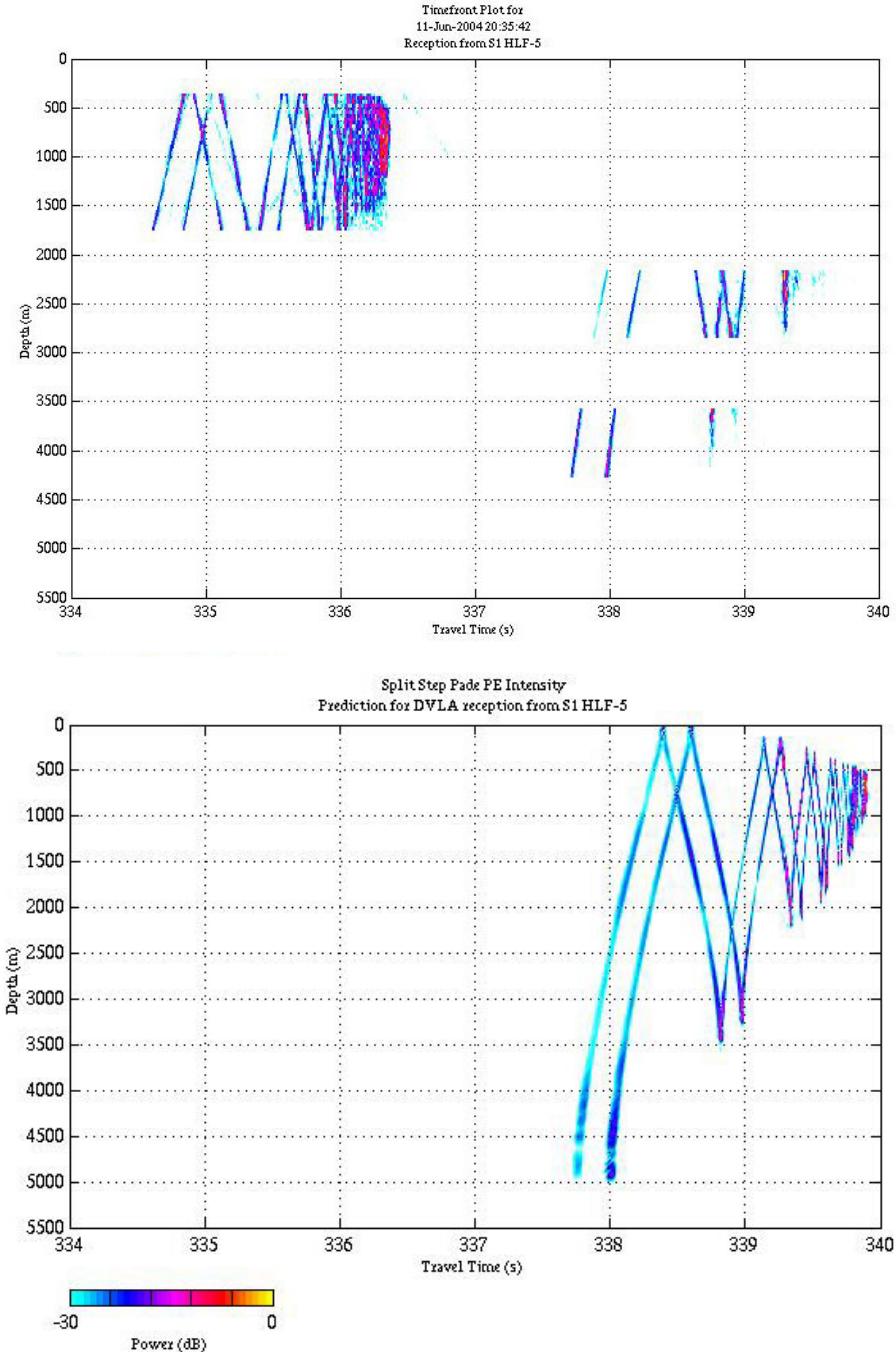
## RESULTS

*250-Hz Receptions.* High signal-to-noise ratios were obtained at the SVLA and DVLA receivers from the moored 250-Hz sources 500 and 1000 km distant. Figure 3 shows the measured timefronts at the SVLA and DVLA from the HLF-5 source 500 km distant, together with predicted timefronts at the DVLA using a range-dependent sound-speed field constructed by combining the Underway CTD (UCTD) data from the upper ocean obtained during the *SPICE04* deployment cruise with historical data from the World Ocean Atlas in the deeper ocean. (The signal arrives at the SVLA first because it is closer to the source.) Even at this relatively short range the measured timefronts at the DVLA extend well into the geometric shadow zones below the lower caustics, with energy visible up to 500–600 m below the predicted caustic depths. (The earliest branches of the timefront at this range extend below the deepest depth sampled by the DVLA, however.) Similar results are found for receptions from the HLF-5 source 1000 km distant from the SVLA and DVLA, except that at 1000 km range the early, surface-reflected branches of the timefront do not extend as far into the geometric shadow zone as the later refracted arrivals (not shown).

It is also notable that even at 500 km the axial finale observed on the SVLA is relatively highly scattered, although not as scattered as at 1000 km range.

*JASA Special Section.* Thirteen papers giving recent results from NPAL-related research were published as a Special Section in the March 2005 issue of the *Journal of the Acoustical Society of America* (Andrew *et al.*, 2005; Baggeroer *et al.*, 2005; Brown *et al.*, 2005; Colosi *et al.*, 2005; Heaney, 2005; Hegewisch *et al.*, 2005; Mobley, 2005; Morozov and Colosi, 2005; Smirnov *et al.*, 2005; Vera *et al.*, 2005; Voronovich *et al.*, 2005; Wage *et al.*, 2005; Worcester and Spindel, 2005). These papers are concerned with a wide range of topics, including statistical measures of amplitude and phase fluctuations at long ranges, the spatial and temporal coherence of the received signal, signal energy redistribution through mode scattering, horizontal refraction, the implications of the theory of ray chaos, the effects of bottom interactions, the characteristics of ambient noise on ocean-basin scales,

and the potential impact of the low-frequency transmissions on marine mammals. The results are summarized by Worcester and Spindel (2005), who served as NPAL co-editors for the Special Section.



**Fig. 3. (Top)** Measured timefronts at the SVLA and DVLA receivers from the HLF-5 source 500 km distant on year day 163 at 20:35:42 UTC, shortly after deployment. The signal arrives at the SVLA first because it is closer to the source. **(Bottom)** Predicted timefronts at the DVLA using a range-dependent sound-speed field constructed by combining the Underway CTD (UCTD) data from the upper ocean obtained during the SPICE04 deployment cruise with historical data from the World Ocean Atlas in the deeper ocean.

## IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic remote sensing of the ocean interior or for other applications. The data from NPAL and ATOC indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetric, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of gyre-scale ocean variability on seasonal and longer time scales.

## TRANSITIONS

*Simple Tomographic Acoustic Receiver (STAR).* SIO and Webb Research Corporation (WRC) collaborated to integrate the newly developed STAR (Simple Tomographic Acoustic Receiver) four-channel receiver and source controller into the WRC swept frequency sources used in the *SPICE04* experiment. The STAR and the integrated STAR/WRC swept frequency source system are much more cost-effective and significantly easier to use than the current generation of acoustic receivers and transceivers employed in long-range propagation and ocean acoustic tomography experiments. Two STAR data acquisition systems are being used in the Windy Island Soliton Experiment (WISE), and a number of other potential users have expressed interest in the STAR receivers and/or the STAR/WRC swept frequency sources.

## RELATED PROJECTS

- (i) J. Mercer, R. Andrew, B. Dushaw, B. Howe, and R. Spindel (APL-UW) have been supported by ONR Code 321OA to conduct *LOAPEX* (*Long-range Ocean Acoustic Propagation EXperiment*) as part of the 2004 NPAL experiment. They are also funded to operate the Kauai source and the SOSUS receivers.
- (ii) A. Baggeroer (MIT) and K. Heaney (OASIS) have been supported by ONR Code 321OA to conduct *BASSEX* (*Basin Acoustic Seamount Scattering EXperiment*) as part of the 2004 NPAL experiment.
- (iii) D. Rudnick (SIO) has been supported by ONR Code 322PO to make SeaSoar and Underway CTD (UCTD) measurements during the 2004 NPAL experiment.
- (iv) A large number of additional investigators and their students have been involved in ONR-supported research related to the NPAL project and have participated in the NPAL Workshops. The Principal Investigators include F. J. Beron-Vera (UMiami), M. Brown (UMiami), N. Cerruti (Washington State), J. Colosi (WHOI), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical Univ.), F. Henyey (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), S. Tomsovic (Washington State), M. Vera (U. Southern Mississippi), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), M. Wolfson (APL-UW), and G. Zaslavsky (NY Univ.).

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